Wind tunnel techniques for investigation and optimization of sailing yachts aerodynamics

WIND TUNNEL TECHNIQUES FOR INVESTIGATION AND OPTIMIZATION OF SAILING YACHTS AERODYNAMICS

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Abstract. This paper presents sailing yacht wind tunnel testing activities carried out in the Politecnico di Milano Twisted Flow Wind Tunnel. In particular test arrangements, procedures and methodologies that have been developed in the CIRIVE Department of Politecnico di Milano University, both for systematic gathering of wind tunnel data and subsequent analysis in order to describe aerodynamic behaviour of the rig and to derive sail force coefficients for VPP, are outlined.

1. INTRODUCTION

Wind tunnel testing on scale models of yachts is a very effective design tool in order to assess different sailplan geometries and to determine the relative performance: in particular for downwind sails, where a large amount of separated flow is present, potential flow methods cannot be used and viscous flow models still require validation of their results and very expensive computational effort.

This paper presents sailing yacht wind tunnel testing activities carried out in the Politecnico di Milano Twisted Flow Wind Tunnel In particular test arrangements, procedures and methodologies that have been developed both for systematic gathering of wind tunnel data and subsequent analysis in order to describe aerodynamic behaviour of the rig and to derive sail force coefficients for VPP use, are outlined.

Finally a different wind tunnel sail testing procedure, based on a hardware-in-the-loop device, developed for the Politecnico di Milano Twisted Flow Wind Tunnel is described. The aim of this new testing procedure is to change the wind tunnel testing process by enabling the test operator to trim the sails to maximise the yacht speed rather than the driving force, which is the current procedure using conventional testing approaches. This device is based on a computer controlled servo-mechanism which allows the yacht model to heel dynamically in the wind tunnel, using both measured sailplan aerodynamic forces and a real time VPP that calculates the yacht dynamic behaviour (including speed) directly from the forces measured in the wind tunnel while the sails are trimmed.

2. TWISTED FLOW WIND TUNNEL

With the purpose of supporting, with a state of the art facility, the world-wide recognised excellence of Politecnico di Milano research in the field Wind Engineering as well as general Aerodynamics, Politecnico di Milano decided to design and build a new large wind tunnel having a very wide spectrum of applications and very high standards of flow quality and testing facilities. The Wind Tunnel has been fully operative since September 2001 and from the first year of operations has been booked for sailing yacht design applications.

2.1 Wind tunnel main characteristics

Figs. 1 and 2 show an overview of the P.d.M. facility: it's a closed circuit facility in a vertical arrangement having two test sections, a 4 x 4m high speed low turbulence and a 14 x 4m low speed boundary layer test section.

A peculiarity of the facility is the presence of two test sections of very different characteristics, offering a very wide spectrum of flow conditions, from very low turbulence and high speed in the contracted 4 x 4m section (I_u<0.15%, V_{max}=55 m/s), to earth boundary layer simulation in the large wind engineering test section.

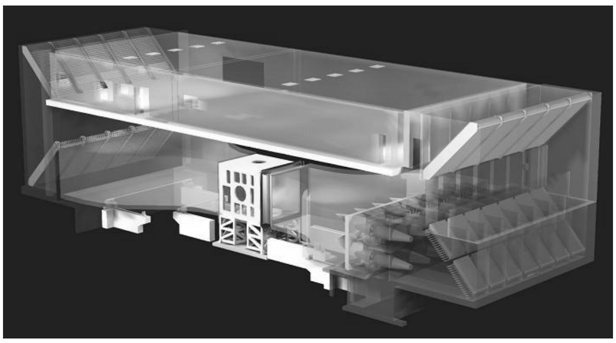

Figure 1. Politecnico di Milano Wind Tunnel (the 14 axial fans array (2 m diameter each) are recognizable on the right lower side)

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Focusing on the boundary layer test section, its overall size of 36m length, 14m width and 4m height allows for very large-scale wind engineering simulations, as well as for setting up scale models of very large structures including wide portions of the surrounding territory. The relevant height of the test section and its large total area (4m, 56m^2) allow for very low blockage effects even if large models are included. The flow quality in smooth flow shows 2% along-wind turbulence. A 13m diameter turntable lifted by air-film technology allows for fully automatic rotation of large and heavy models fitted over it (max load 100,000 N).

The long boundary layer test section is designed in order to develop a stable boundary layer and the flow conditions are very stable also in terms of temperature due to the presence of a heat exchanger linked in the general control loop of the facility. The Wind Tunnel is operated through an array of 14 axial fans organised in two rows of seven 2 x 2m independent cells. 14 independent inverters drive the fans allowing for continuous and independent control of the rotation speed of each fan. This fully computer controlled facility can help in easily obtaining, in conjunction with the traditional spires & roughness technique, a very large range of wind profiles simulating very different flow conditions and different geometrical scales. All the typical various sets of spires have been developed in order to simulate the different wind profiles and an original facility has been recently installed allowing for active turbulence control in the low frequency range.

With reference to yacht sail aerodynamic studies, the boundary layer test section allows for testing large scale models (typically 1:10 -1:12 for IACC yacht model) with low blockage effects at maximum speed of 15 m/s. Due to the large dimensions of the boundary layer section it is possible to test two models at the same time to investigate blanketing effects for tactical purposes.

Concerning the low-turbulence high-speed section, the large dimensions (4 x 4m) and the quite high wind speed (55m/s) enable quite high Reynolds numbers to be reached. In particular, with reference to yacht studies, the high-speed wind tunnel section allows development of specific appendage scale model tests typically on 1:2 scale model for IACC class keel and rudder models.

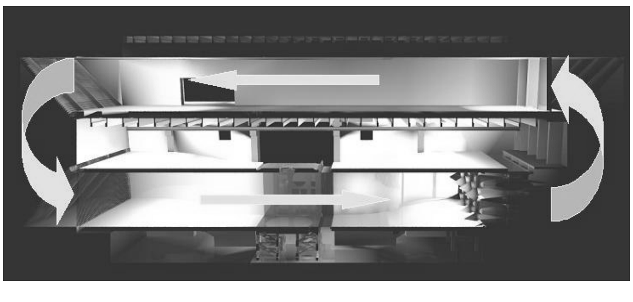

Figure 2. Wind tunnel vertical section

2.2 Twisted flow device

Since the wind speed increases with height due to the boundary layer phenomena and the boat speed is constant, this means that the apparent wind speed incident onto a yacht also increases with height and, in addition, its direction changes, rotating away from the yacht's heading with increased height.

This is a very important topic in wind tunnel testing on sailing yacht scale models, that has to be carefully considered, because the forces developed by the sail plan are due to the apparent wind incident onto the sails and the sail shape and trim is strongly related to the apparent wind profile. Therefore, for proper similitude modelling, the apparent wind velocity shear and twist profile has to be reproduced in the wind tunnel for testing stationary models. In the same way, it has to be reproduced also using CFD codes.

While the variation in wind speed with height can be modelled in the wind tunnel using similar procedures as for conventional wind engineering testing, the twisted flow is a more difficult task to deal with for a stationary wind tunnel yacht model, because the true and apparent wind speeds are coincident.

Other research groups have considered this problem in the past and different solutions have been attempted. A simple approach is to fire the model along a driving rail at a fixed angle through the boundary layer flow generated in the wind tunnel. Such an approach has been taken by the Nottingham vehicle group and the Politecnico di Milano vehicle group in order to obtain force measurements on train and lorries, but many repetitions of each configuration are needed to obtain statistically reliable results. With reference to yacht testing there is also the practical difficulties associated with the sails flexibility and with the necessary sail trimming during the measure: this provided sufficient reasons for the authors not to pursue this approach.

A rather different approach, was used by the University of Auckland Yacht Research Unit [3] based on keeping the model stationary and adding a velocity (corresponding to the opposite of the boat speed) to the velocity profile and hence, introduce twist into the onset flow. Conceptually this could be done by building a boundary layer wind tunnel having porous walls, so that an appropriate amount of uniform flow can be introduced through one side porous wall and the same flow rate withdrawn through the other side one. Another idea is the use of twisted turning vanes at the outlet of a boundary layer wind tunnel: the boundary layer would be used to develop the shear flow and the twisted vanes would be used to develop appropriate twist based on velocity triangles produced from yacht velocity. Flay & al. [3] outlined design activities carried out to create the twisted flow at the University of Auckland; this facility was originally an open jet tunnel with a 6m wide 3m high test section equipped with a cascade of vertical twisted vanes in order to produce twisted flow.

With reference to sailing yacht design, the usefulness of generating a twisted flow for sailing yacht model testing in Politecnico di Milano Wind Tunnel emerged during testing activities carried out by the Mechanical Engineering Department of the P.d.M. with Prada syndicate challenger for the America's Cup 2003.

The Twisted Flow Device concept design had the following basic points:

- To be positioned in the low-speed section
- Guarantee a large area of uniform and controlled twisted flow
- Guarantee persistence of twisted flow state
- Guarantee low turbulence intensity level

The basic idea of the design process is to generate a large-scale vortex with its spin axis aligned with the wind tunnel steady state flow direction, resulting in a twisted flow area corresponding to the model location.

Moreover, basic design requests were the following:

- easy to adjust
- easy to install/remove
- economical solution both in terms of first installation and running costs

The originality of the Politecnico di Milano Twisted Flow Device compared to the other solutions is the central positioning of the device, not occupying the entire tunnel section. In fact, the role of the Twisted Flow Device is just to turn left the lower part and to turn right the upper part of the flow. The side flow not passing though the vanes is allowed to move vertically balancing the flow rate. This concept has been investigated using experimental results obtained from the 1:9 scale pilot wind tunnel model (fig. 3) where a scale model of the twist device has been placed. In order to investigate the experimental results for other configurations, a CFD analysis was also carried out [1].

Figure 3. Pilot 1:9 scaled Wind Tunnel Model

Fig. 4 shows a 3D CFD simulation of the Twisted Flow Device in the tunnel test section, where a large longitudinal vortex is generated. This large-scale vortex guaranties the persistency of twisted flow state behind the device as shown by the path lines coloured by the twist angle.

The wind flow is monitored continuously through several pitot tubes, pressure probes, temperature and humidity probes integrated in the control process of the wind tunnel. In addition to that, specific miniature pitot tubes and hot wire anemometers are on line in order to have a direct and continuous monitoring of the wind characteristics. Cross-correlation techniques can be applied in order to obtain integral scales and coherence evaluations.

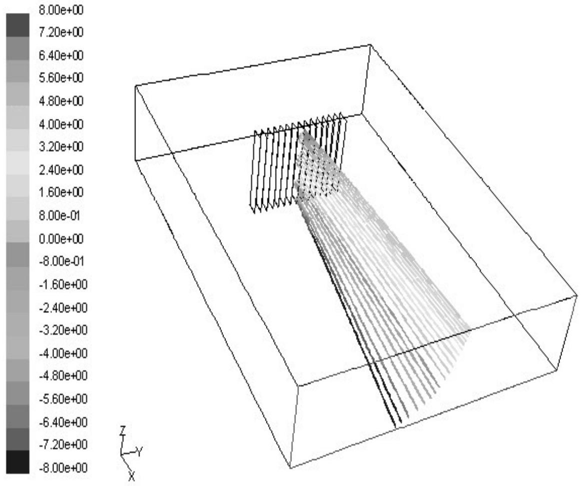

Figure 4. CFD simulation of Twisted Flow Device

3. SAILING YACHT TESTING

3.1 Test arrangements and measurements setup

A complete model, consisting of yacht hull body (above the waterline) with deck, mast, rigging and sails is mounted on a six component balance, which is fitted on the turntable of the wind tunnel (fig. 5). The turntable is automatically operated from the control room enabling a 360° range of headings.

The large size of the low speed test section enables yacht models of quite large size to be used, so that the sails are large enough to be made using normal sail making techniques, the model can be rigged using standard model yacht fittings and small dinghy fittings without the work becoming too small to handle, commercially available model yacht sheet winches can be used and, most important, deck layout can be reproduced around the sheet winch, allowing all the sails to be trimmed as in real life. Moreover the model yacht drum type sheets are operated through a 7 channel proportional radio control system, except that the aerial is replaced by a hard wire link and the usual joystick transmitter is replaced by a console with a 7 multi-turn control knobs that allow winch drum positions to be recorded and re-established if necessary. The sheet trims are controlled by the sail trimmer who operates from the wind tunnel control room. Fig. 5 shows a typical model mounted in the wind tunnel.

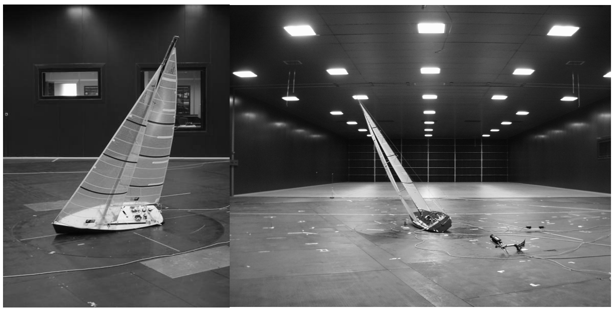

Figure 5. Yacht model in the boundary layer test section

A high performance strain gage dynamic conditioning system is used for balance signal conditioning purposes. The balance is placed inside the yacht hull in such a way that X axis is always aligned with the yacht longitudinal axis while the model can be heeled with respect to the balance.

The wind tunnel is operated at a constant speed after the wind speed profile and wind twist have been properly tuned considering the desired targets, which are previously calculated considering the potential boat performance at different true wind speeds and yacht courses. As previously said the velocity profile can be simulated by means of independent control of the rotation speed of each fan joined to the traditional spires & roughness technique, while the twist can be simulated by twisting the flexible vanes by different amounts over the height range. The wind tunnel speed is most usually limited by the strength of the model mast and rigging and the power of the sheet winches.

Data acquisition can be performed in several ways: the usual procedure provides direct digital data acquisition by means of National Instruments Data Acquisition Boards (from 12 to 16 bits, from 8 differential channels up to 64 single-ended) and suitably written programs according to Matlab standards.

The data acquisition software calculates the forces and moments using the dynamometer calibration matrix. The forces are shown in the virtual panel designed on the computer screen in real time so that the sail trim can be optimised because the effects of trimming the sails on the driving and heeling forces can be directly appreciated.

The model is set at an apparent wind angle and at a fixed heel. After a sail trim has been explored, actual measurements are obtained by sampling the data over a period specified by the test manager (generally 30 seconds) with a sample frequency specified too. An important feature of wind testing procedure is that the model should be easily visible during the tests so that the sail tell-tales can be seen by the sail trimmer. For this purposes some cameras placed in the wind tunnel as well as onboard allow a view similar to the real life situation (fig.6).

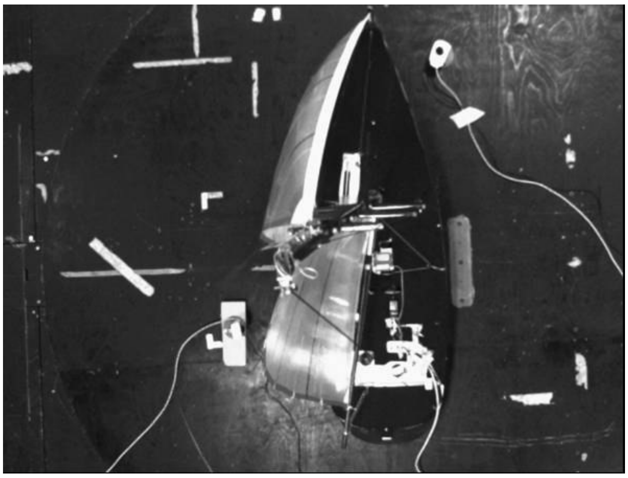

Figure 6. wind tunnel top camera view during testing

In order to correlate force measurement readings and the sail shape and in order to provide input data for CFD calculations, a shape detection system based on infrared camera pictures is under development. Fig. 7 shows the acquisition process of the markers placed on the sailplan.

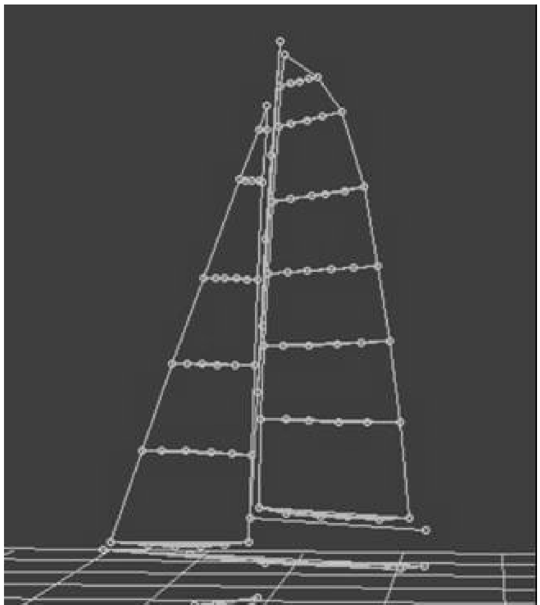

Figure 7. sails flying shape detection process

The raw data in terms of time histories and mean values are stored in files that are used for the detailed data analysis.

3.2 Upwind sails testing procedure

The usual way of analysing data is to compare non-dimensional coefficients [2], to be able to compare the efficiency of sails of different total area at different conditions of dynamic pressure. The first analysis performed is the variation of driving force coefficient Cx with heeling force coefficient Cy.

As an example, fig. 8 shows a comparative plot of Cx versus Cy for the 4 apparent wind angles tested. Each run is shown for each AWA. It can be seen that there are some settings at the highest values of heeling force coefficients where the driving force is lower than the maximum value. These non optimum values were obtained by oversheeting the sails such that the mainsail generally had a tight leech and the airflow separated in the head of the sail.

After having maximised the driving force the sails were adjusted to reduce the heeling force without initially reducing the driving force. The reduction in heeling force was achieved by initially easing the main sheet, to twist the mainsail and minimise flow separation, then adjusting the traveller to reduce the angle of attack of the wind on the main. Envelope curves have been drawn through the test points with the greatest driving force at a given heeling force (fig. 8)

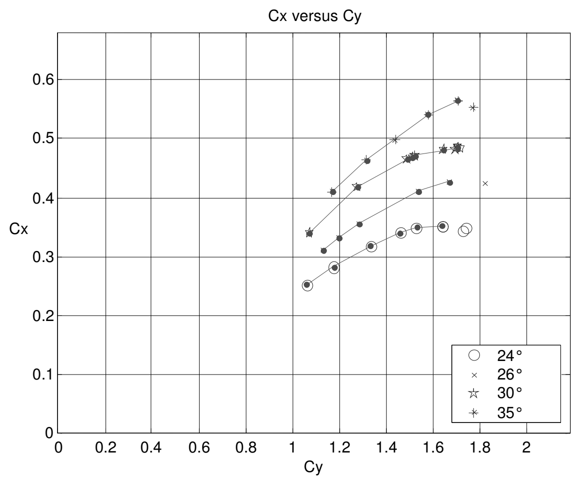

Figure 8 Driving force coefficient vs heeling force coefficient

The heeling moment is also measured in wind tunnel tests and can be used to determine the centre of effort position of the rig. The centre of effort height, Ceh, is obtained by dividing the roll moment by the heeling force component in the yacht body reference system

As an example, a plot of centre of effort height variation with heeling force for different apparent wind angles can be seen in fig. 9 in terms of the ratio between centre of effort height from the boat deck and the fore-triangle height. All the measured values as well as the envelope of the points corresponding to maximum driving force at each heeling force are reported. As can be seen the centre of effort height tends to reduce as the heeling force coefficients reduce. This is explained by the way in which the sails are de-powered to reduce Cy: increasing the twist reduces the loading in the head of the sails and then depowering the mainsail leaving the same genoa trim, which has a lower centre of effort, tends to reduce it.

The centre of effort longitudinal position, Cea, is obtained by dividing the yaw moment by the heeling force component in the yacht body reference system. As an example, a plot of its variation with heeling force for all angles can be seen in fig. 10. All the measured values as well as the envelope of the points corresponding to maximum driving force at each heeling force are reported. In fig. 10 Cea is measured from the origin of the balance which is placed behind the mast. As can be seen Cea moves forward as Cy reduces: this is explained by the way the sails are de-powered as described above.

More information can be extracted from the wind tunnel data by transforming them into lift and drag coefficients (figs. 11-12), and, because both the induced drag and quadratic profile drag vary with the square of lift, it is informative to plot the variation of drag coefficient with the square of the lift coefficient. As an example in figure 13 the drag coefficients against lift coefficient squared for each run performed at different AWA in upright condition is reported.

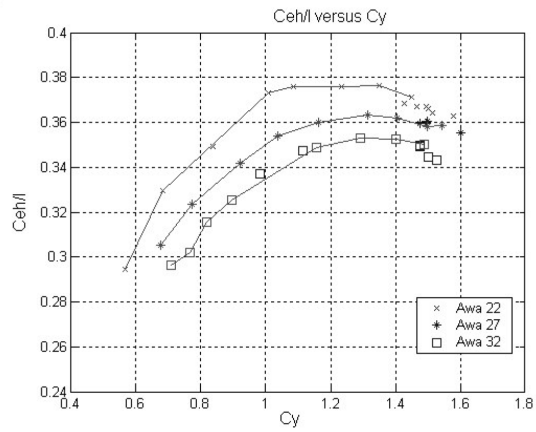

Figure 9. Centre of effort height vs heeling force coefficient

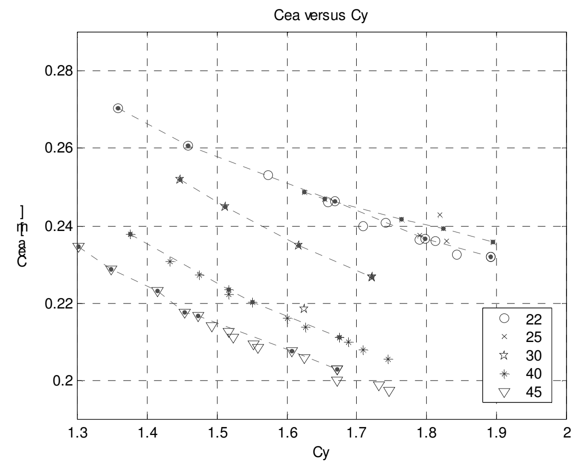

Figure 10. Centre of effort position vs heeling force coefficient

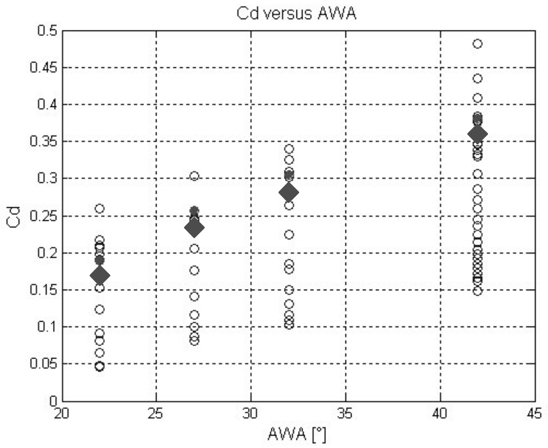

Figure 11. Drag Coefficient : red diamonds correspond to maximum driving force

The red line corresponds to the maximum drive force trimming envelope. As can be seen the envelope line fits points associated with the minimum drag at each lift produced by the sail plan and for reduced values of C_L the drag increases linearly following a straight line.

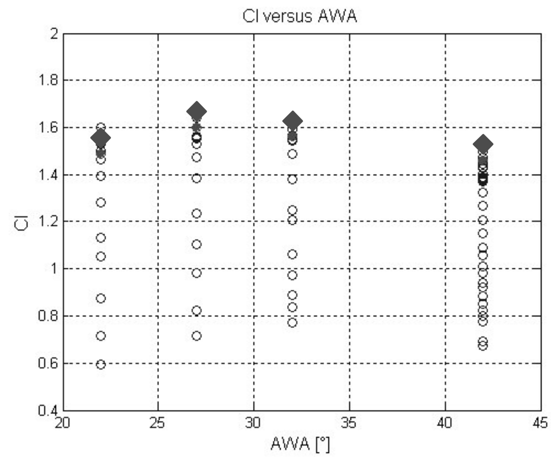

Figure 12. Lift Coefficient : red diamonds correspond to maximum driving force

This linear increase is attributable to the induced drag. The effective height H_{eff} which is a measure of the efficiency of the rig can be determined from the slope of the straight line applying simple aerodynamic theory according to the following equation:

$$Heff = \sqrt{\frac{SailArea}{\pi Slope}} \qquad (1).$$

For higher values for C_L^2 the values of C_D increase more rapidly with C_L^2. This additional drag can be attributed to flow separation from the sails, particularly from the upper mainsail leech. From the intercept of the straight line through data with the zero lift axis, a residual base drag due to windage and parasitic drag can be evaluated.

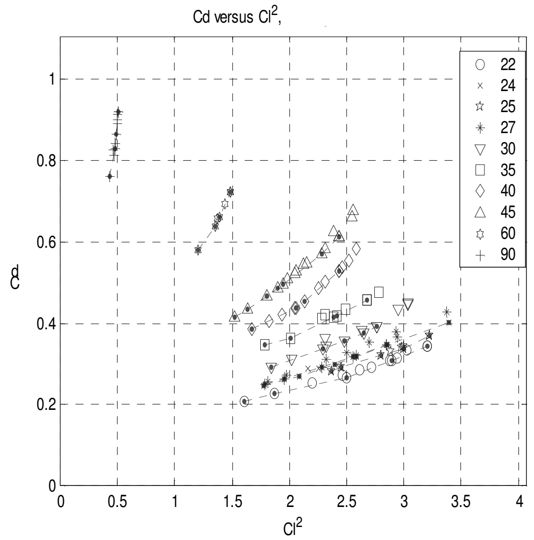

Figure 13. Drag Coefficient vs Lift squared coefficient

In order to introduce the wind tunnel tests results into a VPP a different procedure can be followed. For instance, with reference to the well known IMS VPP aero model, the reduction of C_L with sail flattening is described by the effective rig height:

$$Cd = \frac{C_L^2 SailArea}{\pi Heff^2} \qquad (1)$$

This means that if the maximum drive condition may be associated with some separated flow, taking into account the ($C_{L\ max}$(AWA) and $C_{D\ max\ drive}$(AWA)) point, the actual decline of C_D as $C_{L\ max}$ is reduced following the straight dotted line shown in fig. 14 which results in a drag value higher than it should be.

In order to deal with this phenomenon an alternative equation for the C_D versus C_L^2 relationship could be adopted or defining two different sets of coefficients for the sail plan:

- one for $C_{L\ max}$ Using the standard IMS formulation the corresponding drag will be lower than the actual value which is associated to some flow separation (named $C_{D\ max\ best\ fit\ depowering}$ in fig 14)
- a second one defining the maximum C_L achievable without separated flow. In fig .14 this is called $C_{L\ no\ sep}$) Using this lower curve ($C_{L\ no\ sep}$(AWA) and $C_{D\ no\ sep}$(AWA)) the flat term will correctly model the sail force reduction as sails are eased (see fig. 14)

Moreover the intercept of the straight line with the zero lift axis directly represents the parasitic drag coefficient C_{DO} in the IMS model.

At the end, some runs are performed independently on the bare hull and rigging only (without sails) at different apparent wind angles and in different heeling conditions in order to measure windage. These values are subtracted from each of the measured data points in order to produce the sail force coefficients.

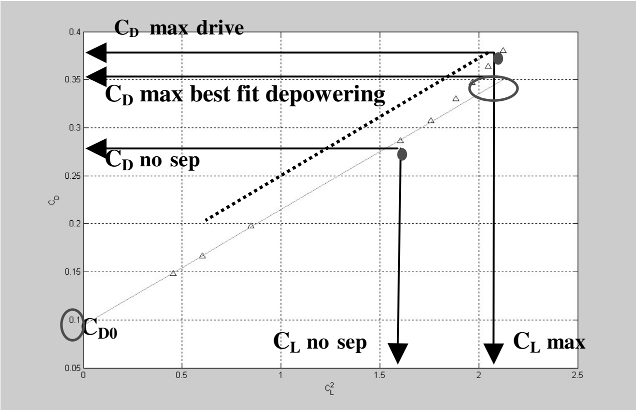

Figure 14.

3.2 Downwind sail testing

On the contrary, with reference to downwind sail testing, because the purpose of the test is generally to evaluate the performance of different sails and to determine the cross-over wind speed at which a smaller sail becomes effective on the yacht the windage of the hull, mast and rigging is not subtracted from the data.

The tests with spinnakers are primarily aimed at establishing the sail forces for downwind sailing so the tests are concentrated on obtaining the maximum driving forces that could be produced by the sails at each apparent wind angle, irrespective of the heeling moment. The spinnakers are set from a pole and remotely controlled winches are connected to allow adjustment of the spinnaker sheet and its lead from the deck, the spinnaker pole height and fore and aft position, and the mainsail sheet. This enables the sail setting to be adjusted in a similar manner to the adjustments made on the yacht in real life. As an example with reference to the mainsail and different spinnakers (symmetric/asymmetric) shown in fig.15, driving force coefficients at different apparent wind angles are reported in fig. 16.

Figure 15.

Each data point represents the best sail setting achieved following a series of adjustments made with the aim to obtaining the maximum driving force.

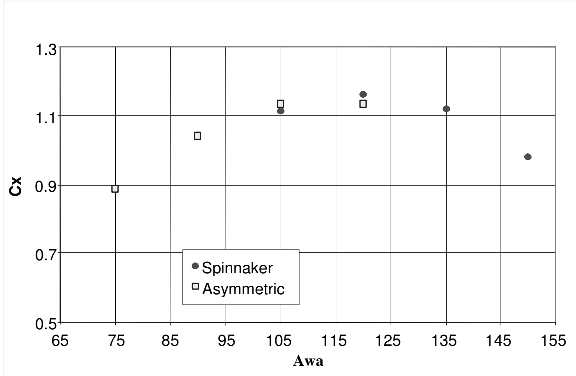

Figure 16. Driving force coefficient vs heeling coefficient

4. SAILING YACHT TESTING: A NEW PROCEDURE

Recently some research activities aimed at improving the simulation of sail modelling in the wind tunnel have been started. In particular a hardware-in-the-loop (HIL) system based on a real time VPP and a servomechanism enabling the model yacht to heel dynamically in respose to the aerodynamic forces in the wind tunnel has been developed. A similar attempt has been also performed at the University of Auckland Wind Tunnel [4].

The real time VPP is based on a 4 d.o.f model of the yacht neglegting the pitching moment and forces up the mast equilibriums, while yaw equilibrium has been taken into account because for depowering and heeling studies rudder angle affects the boat speed significantly. The yacht model is fitted, as for standard testing procedure, with remotely controlled winches to allow for instantaneous sail trimming. The measured forces from the six component force balance (placed inside the model hull) are converted in force coefficients and entered into the real time VPP. The hydrodynamic model of the real time VPP is based on hydrostatic and resistance data for the yacht as required in any conventional VPP. The real time VPP has been designed as an “open system” in such a way it is possible to enter hydrostatic and hydrodynamic data for any hull form including proprietary towing tank data regression curves if available.

The converged solution is displayed on the screen panel allowing adjustment of the sail trim for maximum yacht speed. The resulting heeling angle is then trasmitted to the heel servomechanism and the model is heeled to the desired angle. The real time VPP solver is based on a Gauss-Newton alghoritm, and needs a starting solution to proceed. The heeling servomechanism is based on a linear actuator with a custom-made working range which is driven using a small electic motor fully programmable. The servomechanism is based on an open loop control so that any feedback is needed during the yacht testing procedure. The HIL system gurantees an accuracy to within 0.1 degrees. The servomechanism heels the yacht model and the balance and the air gap beneath the model at all heel angles is sealed using a thin piece of latex. It is therefore necessary to subtract tare forces from model forces as a result of changing heel angle. At the start of the test, the difference of the tare forces from the upright condition are measured over a range of heel angles and a polynomial curve is fitted. At each subsequent measurement, this polynomial is interpolated such that the heeled tare component is subtracted. So the test procedure can be summarised as follows: the heeling mechanism is enabled such that the model is heeled to the angle calculated by the real time VPP. When a suitable trim is achieved, the automated heeling is fixed and the forces are averages over a period previously specified (generally 30 sec). Different wind speeds are used in the real time VPP, generally starting with a low wind speed where the sails are fully powered and as the wind speed is increased, the sails are progressively depowered to maximise boat speed by limiting the heel angle and rudder angle.

As an example in the following some results relevant to a 48 feet cruiser/racer yacht are reported. In fig 17 boat speed versus heel angle obtained from a simulation of 10 knots apparent wind speed at 22° yaw angle is reported. In fig. 18, rudder angle and yawing moment are reported as a function of heel. In each figure the sail trimming performed from one sailing point to the subsequent is reported.

As a comment it can be shown that oversheeting leads to an overheeled condition resulting in a lower yacht speed. It should be pointed out that if the standard testing procedure described at par. 3.2 is used, at each yaw the whole Cx-Cy matrix has to be acquired at different heel angles in order to provide aero data to a VPP, which chooses the best values for a defined full scale wind condition. This testing method is very effective because Cx-Cy data producing the best boat performance are directly identified.

As an example fig 19 shows a comparison between the two methods at 22° heading angle. In particular blue lines represent Cx versus Cy curves obtained with the model heeling device disabled for the upright condition (H0) and for the 30° heel (H30) respectively: these data should be subsequently processed using an off line VPP. In the same figure green diamond spots have been directly obtained using the real time VPP, with the heeling device enabled, corresponding to the best yacht performance at 5 and 20 knots apparent wind speed. For each point the corresponding heel angle and boat speed are reported too.

As can be seen, at low wind speed yacht heel is very limited, sails are fully powered and driving force coefficient is close to the maximum driving at upright condition. On the other side, in breezy conditions the obtained point is closed to the 30° heel line and boat maximum speed is obtained with sails de-powered.

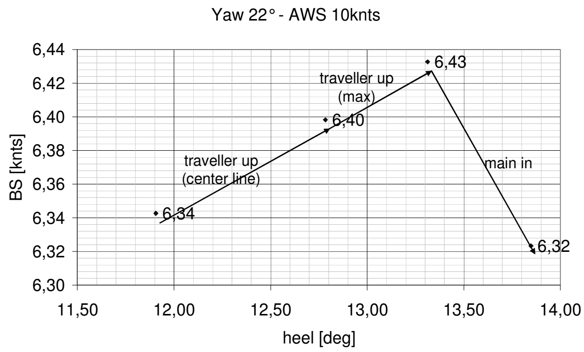

Figure 17.

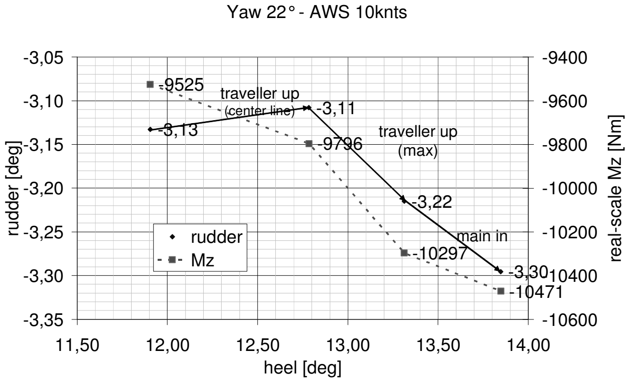

Figure 18.

Finally, the development of a sail selection charts is the sails are built and, it is both time consuming and angle expensive. The wind tunnel based on real time VPP testing procedure offers a suitable method of determining the crossover points quickly in the wind tunnel allowing to see the useful range of a particular sail.

Furthermore this testing method is very effective when canting keels or water ballast options are considered to provide stability for particular sailing conditions, because it is possible to ensure that the optimum settings for the particular sail are tested.

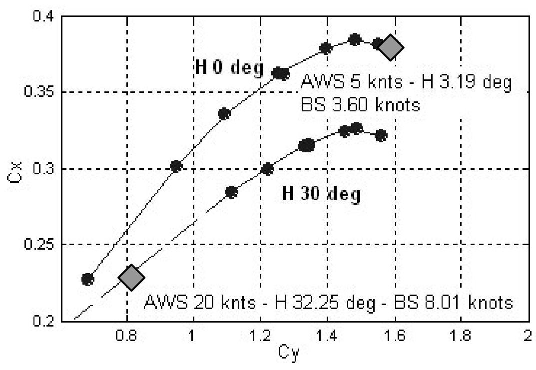

Figure 19.

5. CONCLUSIONS

In this paper an overview of test arrangements, procedures and methodologies developed to describe the aerodynamic behaviour of the rig and to derive sail force coefficients for VPP use are outlined. Moreover a recently developed testing procedure, based on a computer controlled servo-mechanism which allows for dynamic heel of the yacht model in the wind tunnel, using both measured sailplan aerodynamic forces and a real time VPP has been described.

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